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Phase change material (PCM) storage for free cooling of buildings—A review

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ABSTRACT

Globally, buildings are responsible for 40% of the total world annual energy consumption which is responsible for one-third of green house gas emissions around the world. A significant portion of this energy is used for lighting, heating, cooling, and air conditioning purposes in buildings. Increasing awareness of the environmental impact of green house gas emissions and CFCs triggered a renewed interest in environmentally friendly cooling, and heating technologies for buildings. Free cooling of buildings may be seen as an alternate to compressor based air conditioning systems used for the buildings. In free cooling, nighttime cold is accumulated in storage material and extracted when needed. Latent heat storage using phase change materials (PCMs) can be used for free-cooling purposes due to their high storage density. In free cooling, using PCM as storage material, cool air during night is used to solidify the PCM and the accumulated cold is extracted during the hot day times. In this article a detailed review of work conducted by different researchers on PCM based free cooling is presented. Major challenges being faced in the design of PCM based free cooling system such as phase change materials; their thermo-physical properties and the geometry of encapsulation are elaborated and discussed in detail. Also the parameters effecting the charging and discharging of PCM, effect of phase change temperature and climatic conditions on thermal performance of the free cooling system are also discussed. Potential reduction in CO_2 emissions due to the applicability of free cooling systems in residential and commercial buildings is also discussed in this article. This paper also provides a comprehensive list of the PCMs currently being used and that can be used potentially for free cooling applications. At last, this paper also presents some current problems needed further research in this area.

Contents

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1. Introduction

Globally fossil fuels are dominating the world energy market and it is predicted that fossil fuels will continue to produce 75–80% of the world's primary energy by 2030. [1]. Worldwide environmental concerns (climate change, global warming, etc.) due to their usage and finite reserves of these fuels have increased attention to reduce their consumption in all economic sectors of the world. About 30–40% of the world primary energy is consumed by the building sector and is responsible for one-third of green house gas emissions (responsible for global warming) around the world [2]. In buildings, a major portion of the energy is used by heating and cooling applications and it is estimated that 10–20% of this energy is used by HVAC equipments [3]. Global concern of the environmental impacts of the fossil fuel usage has prompted the interest to search and use passive techniques for heating and cooling of the buildings [4].

Passive cooling of the buildings refers to those technologies or techniques which are used to cool the building interior with or without minimum electricity usage. Term "passive" does not exclude the cooling technologies or techniques that use fan or pump when their application might enhance the cooling performance according to some researchers [5–8]. Buildings can be cooled passively while using several natural heat sinks like ambient air, upper atmosphere, under surface soil etc. Therefore, the passive cooling techniques are classified according to the natural source from where the cooling energy is derived. The classification of the passive cooling techniques is shown in Fig. 1 [6,9] and explained briefly below.

1.1. Evaporative cooling

Evaporative cooling is the technology for the cooling of air by the evaporation of water. When water evaporates, it absorbs heat from the surrounding air and consequently the air is cooled. After water evaporates, it enters the air as water vapor and transmits the heat absorbed during evaporation back to the air in the form of latent heat. Therefore, the air is humidified, and the total heat, or enthalpy, of the air hardly changes. The humidified and the cooled air is used in the building for cooling purpose and the process is known as direct evaporative cooling which is most suitable in dry and hot climates [10]. In indirect evaporative cooling of the air, adding moisture to the air is avoided by separating water and air, which makes it more attractive in humid climates [9,10].

1.2. Soil cooling

Hot ambient air can be cooled down by circulating it through the heat exchanger buried at the depth of 2–3 m below the earth surface [11]. The earth surface holds a stable temperature, which is below the average ambient temperature, at the depth of 2–3 m approximately. Soil cooling implemented in desert climate may reduce the peak indoor temperature by 3 °C during hottest summer months [12].

1.3. Ventilation cooling

Ventilation techniques can be used to improve the comfort conditions of the buildings. One of these techniques is to provide the physiological cooling effect to the building occupants by introducing fresh cool ambient air inside the building at higher air velocity. The physiological cooling effect is provided by opening the windows or doors, through cross ventilation or by electric fans to let the ambient air in and thus providing the higher indoor air speed and making building occupants feel cooler. The physiological cooling is normally used when ambient temperature is lower than the indoor temperature [6,7,13].

Another ventilative cooling technique is known as the nocturnal ventilative cooling [6,7], in which building mass is cooled down during night through ventilation which serves as a heat sink during the following hot day time.

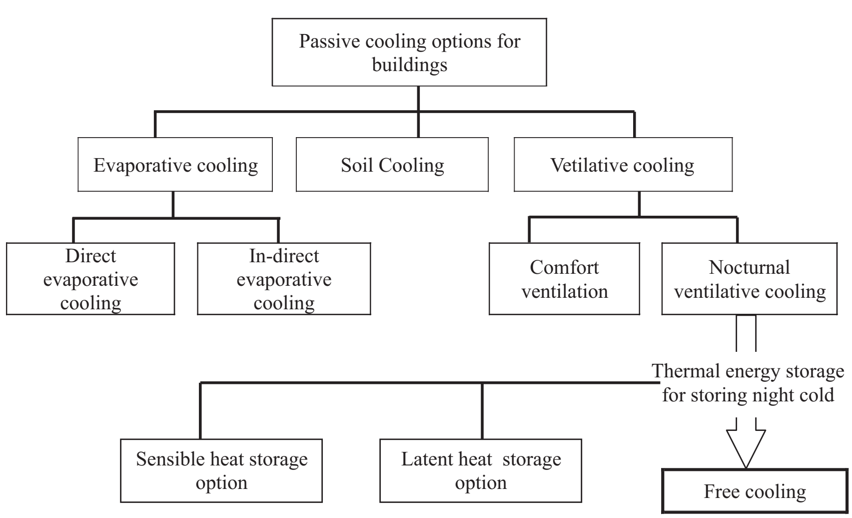


Fig. 1. Classification of passive cooling techniques for building applications.

Nomenclature

a_p	superficial particle area per unit bed volume m^{-1}
A_s	cross sectional are of air channel, m^2
A_{HT}	heat transfer surface area of the boundary node, m^2
c_{app}	apparent heat capacity of PCM, J/(kg K)
c_{ps}	specific heat of liquid or solid, PCM J/(kg K)
$C_{p\ air}$	heat capacity of air, kJ/kg-K
c_p	specific heat of heat transfer fluid, J/(kg K)
d	sphere diameter, m
h	heat transfer coefficient for air, W/m^2-K
H	total volumetric enthalpy, kJ/m^3
L	LHTES length, m
$\dot{m}_{air}$	mass flow rate of air, kg/s
m_{PCM}	mass of PCM in DSC instrument, kg
t	time, s
T	temperature, °C
T_a	LHTES ambient temperature, °C
T_{air}	temperature of air, °C
T_{pcm}	PCM temperature, °C
u	velocity, m/s
U_w	overall wall heat transfer coefficient
$\dot{v}_{air}$	volume flow rate, m^3/s

Greek symbols

α	heat transfer coefficient, W/m^2-K
ε	bed porosity
Θ	PCM temperature, °C
ρ_{pcm}	density of PCM, kg/m^3
λ_f	effective thermal conductivity in the radial or axial direction, W/m-K
λ_{PCM}	thermal conductivity of PCM, W/m-K
λ	latent heat of PCM, kJ/kg
κ_{air}	thermal conductivity of air, W/m-K
κ_{pcm}	thermal conductivity of PCM, W/m-K

1.4. Free cooling

In free cooling, a storage medium is used to store the cold when ambient temperature is lower compared to the room temperature and the stored cold is extracted from the storage medium whenever it is needed using an electric fan [14,15]. Storage medium for free cooling is normally in the form of sensible and latent energy type.

The main difference between free cooling and the nocturnal ventilative cooling is that in later the building structure (like walls) act as the storage medium while in free cooling technique, a separate thermal storage unit is used for the storage of the cold and a mechanical device like fan is used to store and extract the cold from the storage unit. Advantage of free cooling over the nocturnal ventilative cooling is that the accumulated cold can be extracted whenever it is needed by circulating ambient or room air through storage unit.

A lot of published literature is available regarding PCM and their usage in buildings but the current review is focused explicitly to review the published literature on free cooling studies and storage medium specifically phase change storage medium for the cooling of buildings.

Free cooling working principle along with the published theoretical and experimental studies are figured out in Section 2. Climatic applicability of free cooling of the buildings is discussed in Section 3. Section 4 focuses on the economical and environmental feasibility of free cooling systems and their ability to reduce the CO_2 emissions are also outlined in this section. Section 5 discussed the indictors that have been used to access the cooling potential of the free cooling systems. Parameters influencing the thermal performance of free cooling system are discussed in Section 6. Section 7 discusses the criteria to select the melting point of PCM to be used for free cooling applications. PCMs which have been frequently used for free cooling purposes and PCMs which can be the possible candidate for free cooling applications are addressed in Section 8. PCM encapsulation techniques are discussed in Section 8. Numerical methods to study the heat transfer mechanism in PCM and heat transfer fluid related to free cooling studies are discussed in Section 9. Key issues related to PCM and free cooling studies are discussed in Section 10 while a summary of free cooling studies is outlined in Section 11 and further research areas are elaborated in Section 12.

2. Free cooling of the buildings during summer season

Thermal energy storage is the vital part of the free cooling system which is used to store the ambient cold to be used later during hot day time. Generally thermal energy, for free cooling, is stored either by changing the internal energy of the storage material (sensible heat storage), by changing the phase of the storage material (latent heat storage) or the combination of the these two [16,17]. Latent Heat Thermal Energy Storage (LHTES) by Phase Change Materials (PCMs) is preferred over other storage techniques due to its high energy storage density and isothermal storage process. Phase Change Materials (PCM) are substances with high heat of fusion, melting and solidifying at a certain temperature and are capable of storing and releasing large amount of thermal energy at a certain phase change temperature. Thermal energy is absorbed or released as the material changes its phase from solid to liquid or from liquid to solid.

2.1. Free cooling working principle

The working principle of PCM based free cooling for buildings is shown in Fig. 2 which consists of following two modes of operation:

- *Charging process* (*solidification of PCM*): Charging process is carried out during nighttime when ambient temperature is lower compared to room temperature shown in Fig. 2a. The cool ambient air flows through storage unit and takes away heat from liquid PCM which starts solidifying at certain constant temperature. An electrically driven fan is used to remove the heat from PCM [18]. Charging process continues until the ambient temperature is lower enough than the melting/solidification temperature of PCM.
- *Discharging process* (*cooling of air*): Cold stored in PCM is discharged when room temperature rises above the comfort limit shown and explained in Fig. 2b. Hot air which is to be cooled passes through the PCM storage unit and PCM (which is in solid state after charging operation) absorbs heat from the air. The air thus cooled to comfort temperature from the storage is delivered to the living space. PCM absorbing heat from air, starts converting from solid to liquid phase at certain constant temperature. This process is called "discharging process [18]."

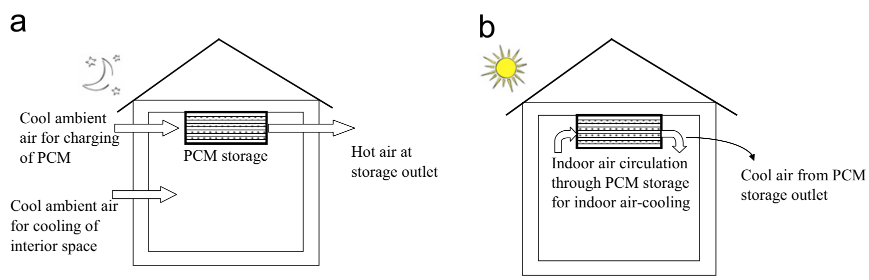


Fig. 2. Free cooling working principle [18]. (a) Charging process (working of PCM storage during night time) and (b) Discharging process (working of PCM storage during day time).

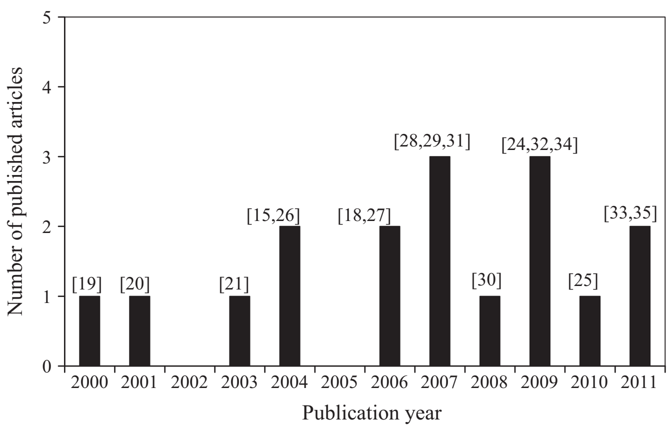


Fig. 3. Number of publications per year.

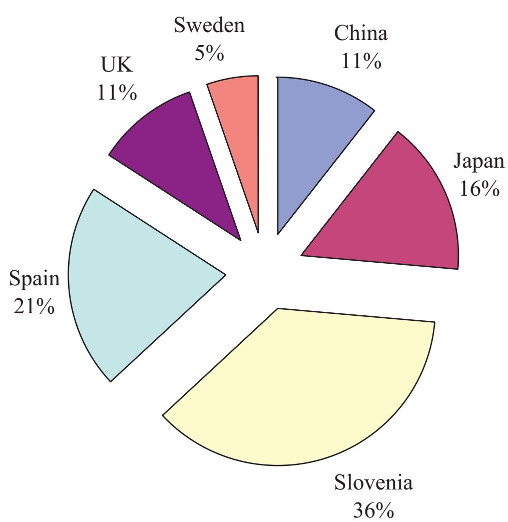


Fig. 4. Research on PCM based free cooling around the world.

2.2. Free cooling published literature

According to the published articles PCM based free cooling of buildings is not very old topic as the first study was published in the year, 2000 shown in Fig. 3. The published articles on free cooling subject is shown in Fig. 3 which is based on the articles found only in Elsevier journals excluding the conference papers to avoid any duplication.

It can be seen from Fig. 3 that in the last 3 and 4 years the topic has attracted the researchers interest as in the years 2007 and 2009 more studies were published compared to the year 2000, 2001 and 2002 where only one study was found.

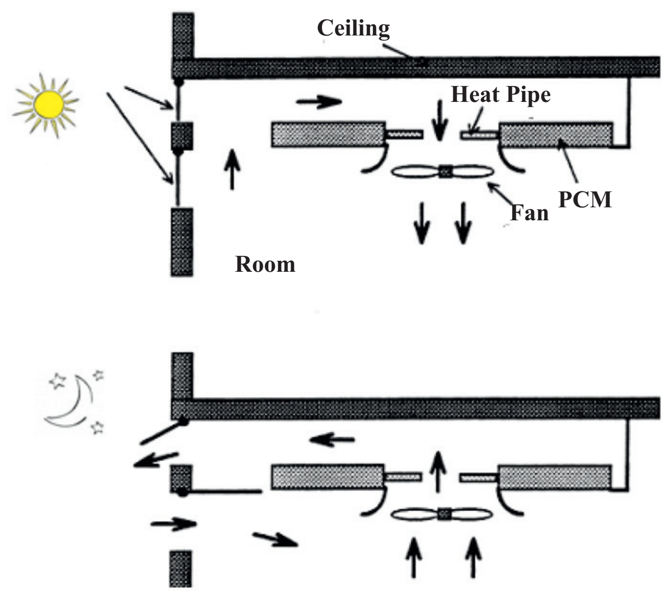


Fig. 5. Heat pipe embedded in PCM storage unit for free cooling purpose [19,20].

According to the published literature [19–35], the regions around the world where PCM based free cooling is either implemented or studied are shown in Fig. 4. It can be seen from Fig. 4 that most of the studies on free cooling are conducted in Europe (~73%) with very few in Asia like Japan and China. One more observation from Fig. 4 is that most of the studies are conducted for the developed countries especially Europe where energy efficiency, energy conservation and climate change are much discussed topics. Very few studies are found for the developing countries and none of the study has been observed for USA

2.3. Theoretical and experimental studies on PCM based free cooling of buildings

Very first study published about the cooling of buildings based on free cooling principle was conducted by Turnpenny et al. [19] using heat pipes embedded in PCM storage unit shown in Fig. 5. PCM used for thermal energy storage was salt hydrate ($Na_2SO_4 \cdot 10H_2O$) with melting point of 21 °C. PCM which was melted within 9 h with the temperature difference of 5 °C between discharging air and melting temperature of PCM. The system provided the heat storage of 240 Wh for about 8 h. Heat storage rate was calculated using the following relation:

$$Q = \frac{L_s}{t} \quad (1)$$

where L_s is total latent heat capacity of the PCM (J) and t is the total time taken by the whole volume of PCM to change the phase.

It was observed that higher temperature difference between PCM melting point and charging air was beneficial to freeze the PCM in the specific time period. Otherwise, high air flow rates would be needed to solidify the PCM completely in the given time span.

A prototype free cooling system based on the findings of Turnpenny et al. [19] was installed and tested in a typical office by Turnpenny et al. [20] shown in Fig. 6. The latent heat storage rate was 1000 Wh for 2–3 h time period with the heat transfer rate of 200 W. The results indicated that the free cooling system can provide heat storage enough to prevent the overheating of the office building during typical UK summer conditions. In addition, it was observed that the proposed free cooling system had the potential of reducing the CO_2 emissions by 430 t per year if replaced by the conventional air-condition units in 2000 offices around UK.

Night Ventilation coupled with PCM Packed Bed storage (NVPPB) was studied by Yanbing et al. [21]. Fatty acid was used as PCM, developed by the authors having density of 850 kg/m^3. The schematic of NVPPB is shown in Fig. 7. The PCM storage was placed in the space between the hung ceiling and the floor. COP of the whole system (defined as the ratio between the cold discharged from PCM and the fan power used for discharging the cold and) was found to be 80. The maximum amount of the cold discharged from PCM to room was ~300 W during the hot day times and during nighttime it was ~1 kW. Therefore, NVPPB technique increased the comfort level of the buildings during daytime as 300 W cold was discharged from PCM to the living room.

A laboratory scale experimental setup was designed by Marin et al. [22] to study the application of PCM in free cooling systems shown in Fig. 8a and b. Commercially available PCM, RT25, was encapsulated in flat plate type heat exchanger shown in Fig. 8b. The encapsulation plates for PCM were made with methacrylate to allow phase change visualization. The thermal performance of the storage system was evaluated using the following energy

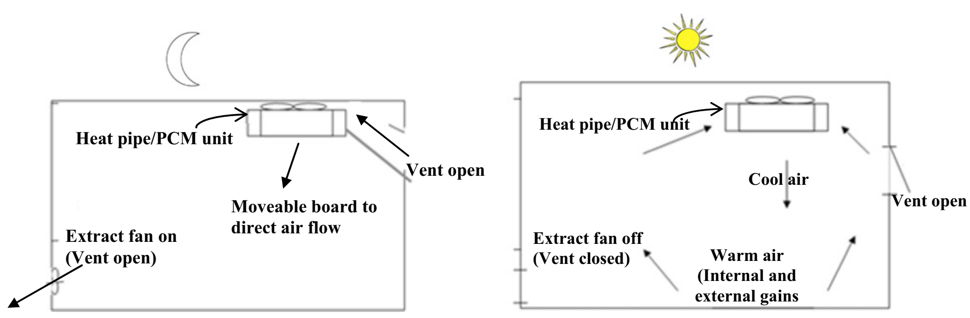


Fig. 6. Schematic view of the prototype PCM–heat pipe free cooling system installed in UK office [20].

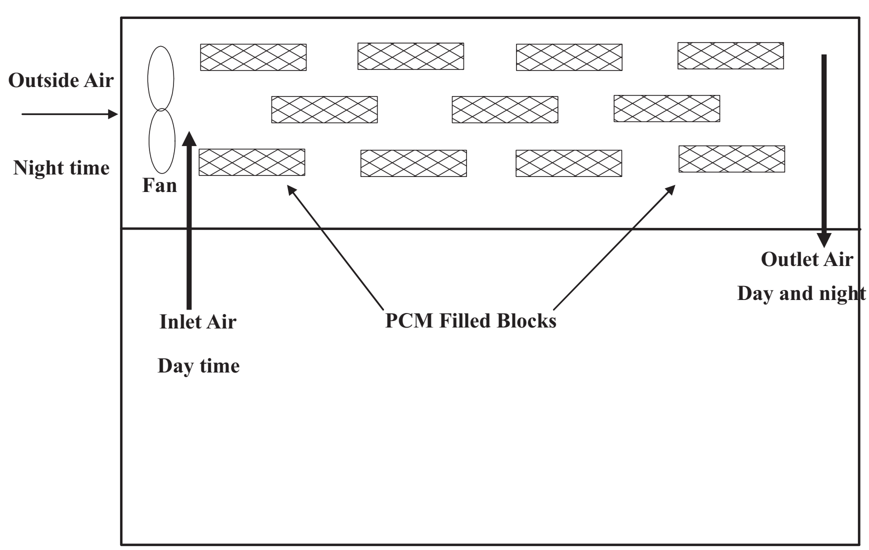


Fig. 7. Night ventilation with packed bed PCM storage system [21].

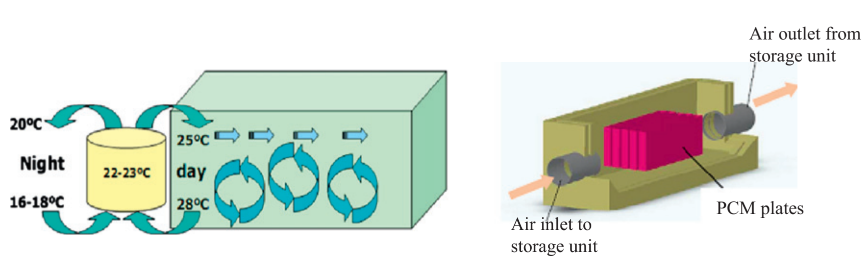


Fig. 8. Free cooling concept by Marin et al. [22].

balance:

$$\dot{Q} = \dot{Q}_{env} + [\dot{m}C_p(T_{inlet} - T_{outlet})]_{air} - \frac{dU_{ins}}{dt} \tag{2}$$

In Eq. (2) first term on R.H.S. shows the heat loss to the environment from storage, 2nd term is the change in the enthalpy of the air as it passes through the storage unit and last term explains the heat losses from the insulation of the storage. To evaluate the thermal performance of the storage, parameters studied were energy to volume ratio, air flow rate through storage and the melting point of the PCM. Thinner layers of PCM slabs, higher temperature difference between inlet air and melting temperature of the PCM and the higher air flow rate triggered the solidification of the PCM.

According to the study, aluminum fins attached to the rectangular PCM container can be advantageous to increase the thermal power of the PCM cold storage. PCM cold storage. Aluminum fin, filled with 3.6 kg of PCM (RT20) kept the hot the ambient air (∼27 °C) to ∼24 °C for more than 2 h with the air flow rate of 7.8 l/s. For large spaces, the cooling load is higher and higher air flow rate is needed. Therefore, connecting the cold storages in parallel can fulfill the required cooling load [23–25].

Takeda et al. [26] studied a PCM packed bed thermal storage to reduce the ventilation load of the building for Japanese climatic conditions. PCM storage was placed in the ventilation system of the building operating on the free cooling concept. The room temperature was set to 26 °C for cooling. Whenever ambient temperature was lower than 26 °C cold air was supplied to PCM to charge it (solidify the PCM). The cold was discharged from PCM when room temperature rose from the set value. An experimental setup consisting of a rectangular ventilation duct of 900 mm length and 140 mm width was constructed as shown in Fig. 9. Commercially available PCM granules "GR" were used as the storage material [26]. The phase change temperature of PCM was in the range of 22.5–25.0 °C. The results showed that the outlet air temperature from PCM storage always remained stable and in the phase change range during discharging process. Ventilation load was reduced from 46% to 62%, using PCM storage unit in different cities of Japan.

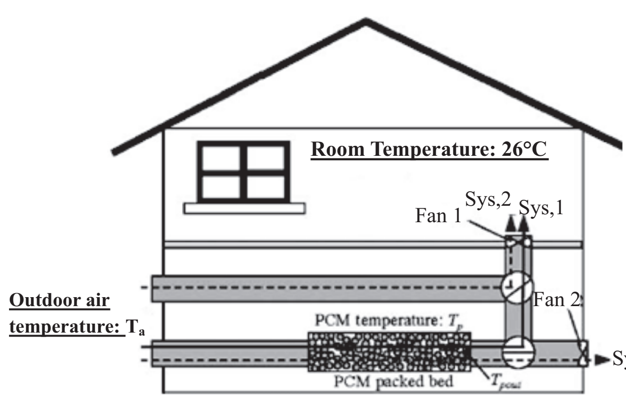


Fig. 9. Ventilation system utilizing PCM thermal energy storage [26].

An innovative floor integrated air condition system was proposed by Naganao [28] in which the cooling load during daytime was shared by commercial air conditioner and by releasing the cold accumulated in PCM storage. The proposed air conditioning system is shown in Fig. 10a. PCM was embedded under the floor in the form of granules with diameter of several micrometers. Commercially available PCM granules, with the diameter of several micrometers containing paraffin were used as the storage medium. Room temperature was set at 28 °C. The cold stored in PCM during nighttime reduced the cooling load up to 92% on the following day as compared to the conventional storage system which reduced the cooling load up to 50%.

Cylindrical thermal energy storage unit filled with spherically encapsulated PCM (RT20) shown in Fig. 11 was used to determine the free cooling potential by Arkar et al. [29–31]. PCM storage was integrated into the ventilation system of the existing building. For efficient performance of storage unit, PCM melting temperature was kept in the range of ±2 °C of the operating temperature.

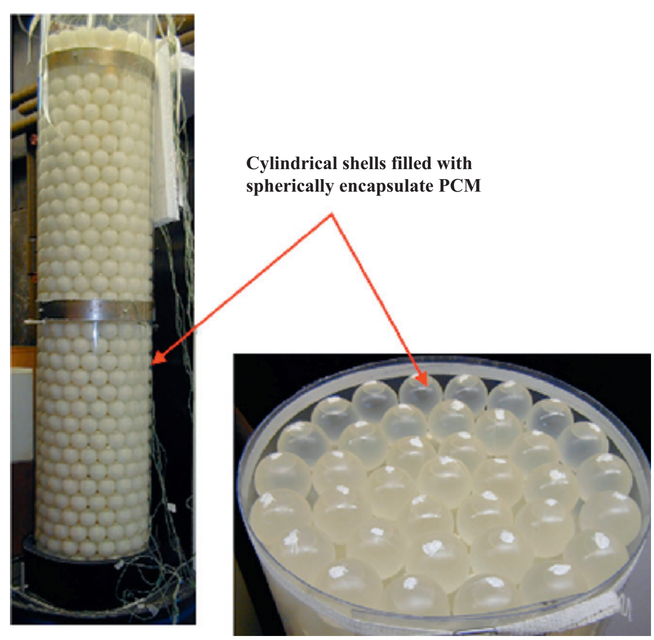


Fig. 11. Cylindrical storage filled with spherically encapsulated PCM [29–31].

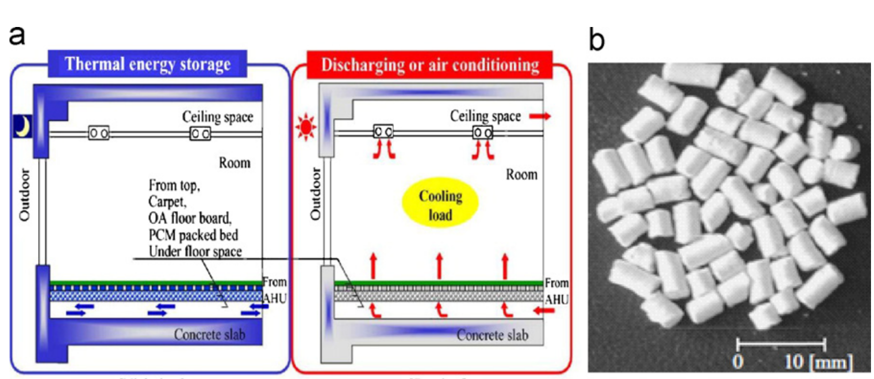


Fig. 10. PCM embedded in floor used for free cooling.[27,28]. (a) Ventilation Scheme (b) PCM Granules.

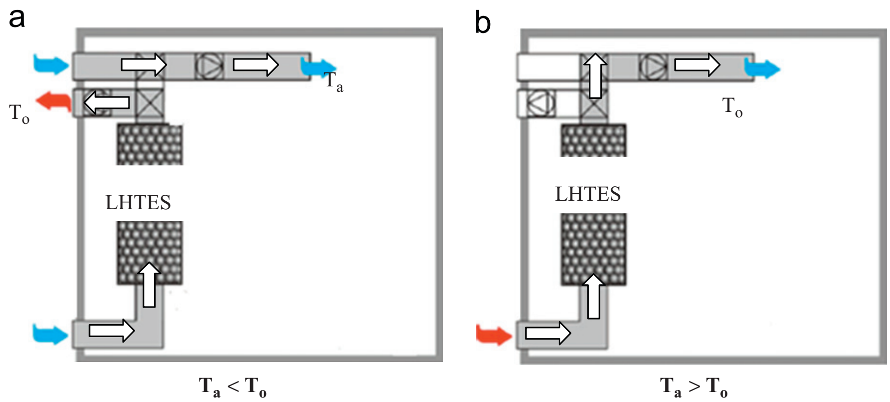


Fig. 12. PCM storage for free cooling of buildings: (a) daytime operation and (b) nighttime operation [30].

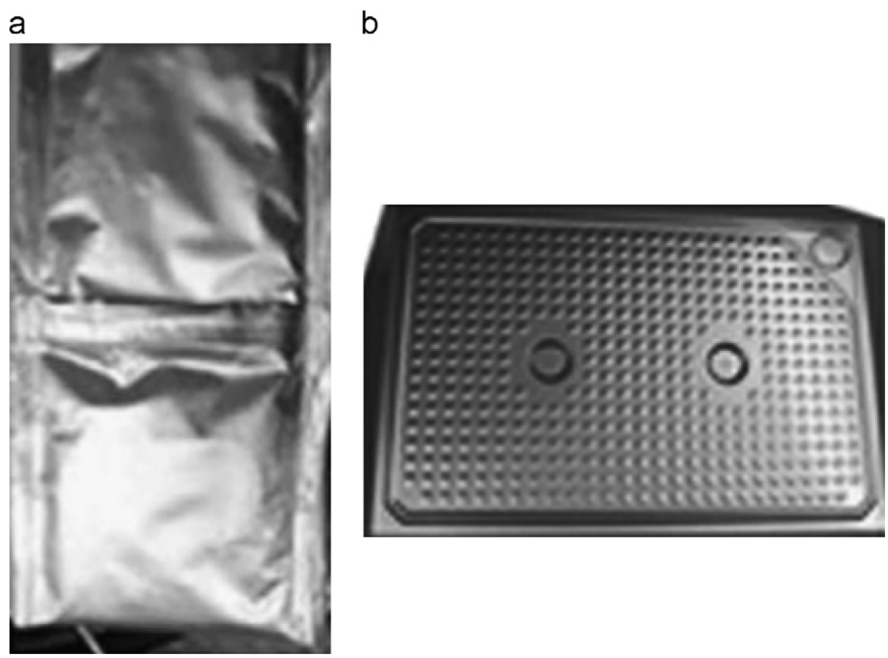


Fig. 13. Prototype heat exchangers for free cooling applications [32,33]. (a) Prototype 1: aluminium pouches filled with organic PCM and (b) Prototype 2: aluminium panels filled with inorganic PCM

The mass of PCM equal to 6.4 kg/m^2 of floor area was found optimal [29]. Cooling Degree Hours (CDH) was used as an indicator to assess the performance of the PCM storage. Working of the free cooling for building ventilation and cooling used by Arkar et al. [29] is shown in Fig. 12. The study concluded that about 6.4 kg of PCM per m^2 of floor area with air flow rate of 1.0–0.7 m^3/h per kg of PCM will be optimal to ensure maximum cooling degree hours [29].

Based on the findings of Marin et al. [22] (thinner layers of PCM in rigid capsulation are advantageous for free cooling application) two real-scale prototypes air–PCM heat exchangers were developed and tested by Lazaro et al. [32] for free cooling applications. Prototype 1 was designed using aluminum pouches filled with inorganic PCM (Fig. 13a) while prototype 2 used the aluminum panels filled with organic PCM (Fig. 13b). Air inlet and outlet temperatures were used to estimate the cooling power of the heat exchangers. Higher cooling power was observed in heat exchanger with aluminum panels (Fig. 13b) compared to the heat exchanger containing aluminum pouches due to the fixed thickness of PCM layers and resulting reduced heat transfer resistance inside PCM in aluminum panels. PCM leakage was also observed in aluminum pouches due thermal expansion of PCM in liquid phase. Heat exchanger with aluminum panel was recommended

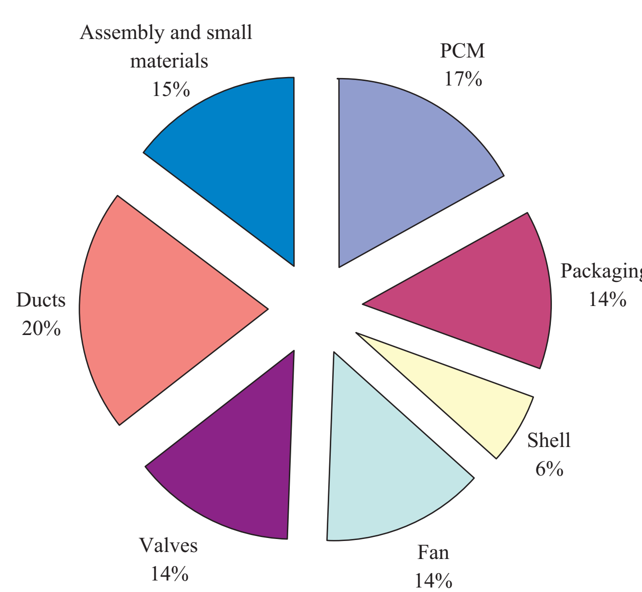


Fig. 14. Total cost of the free cooling system in percentage [22].

to be used for free cooling applications due to higher cooing rates and no PCM leakage [32,34].

In the above discussion [32], the aluminum panels were filled with organic PCM their behavior with inorganic salts was not mentioned which exhibits the corrosion behavior but higher thermal conductivity.

Applicability of the free cooling system was studied by Waqas and Kumar [36] for dry and hot climatic conditions. It was observed that the PCM storage unit can be used as a heat sink to keep the ambient air temperature within the comfort limits during the hot daytime in summer season. Also when the PCM melting temperature is equal to the comfort temperature of the hottest summer month, the storage unit performance is maximized for all the months during summer season.

A parametric study was conducted by Tzivanidis et al. [37] for space cooling using cold night temperature. Cold water during time was flowing within regularly arranged pipes embedded in a layer of phase change material (PCM) during nighttime, located among the structural layers of the ceiling. According the study results main parameters that should be given importance during system design are pipe spacing, PCM layer thickness, pipe depth within the ceiling, cooling water inlet temperature, night cooling duration and PCM properties (thermal conductivity, phase change heat and ends of phase change temperature range).

3. Climatic applicability of free cooling of the buildings

The applicability of the PCM based free cooling potential for reducing the ventilation or cooling load (CDH) of the buildings depends mainly on the diurnal temperature range or the amplitude of the ambient air temperature swing [30] rather than average ambient temperature of the region [26]. Therefore, free cooling of buildings coupled with PCM storage unit performs efficiently in the climatic conditions where the diurnal temperature range is between 12 and 15 °C [6,38]. For climates where the diurnal temperature range is less, coupling of PCM storage unit with free cooling will require a careful design consideration [15] including selection of appropriate PCM and appropriate PCM capsulation.

Mainly ambient air temperature data is needed to analyze the climatic potential for free cooling of the buildings before its physical implementation. Hourly ambient air-temperature data can be obtained from the meteorological department of the study area. The commercially available database Meteonorm [39] also provides the semi-synthetic meteorological data for 7400 stations around the world. Hourly air temperature data generated by Meteornom is based on the measured long-term monthly mean values (mainly 1961–1990) [39,40]. Hourly ambient air-temperature data from the Meteornom data has been used by many authors [29–31,36] to study the applicability of PCM based free cooling of buildings for different climatic conditions.

4. Economical and environmental feasibility of free cooling systems

An economical feasibility analysis of the free cooling system conducted by Marin et al. [22] is presented in Fig. 14. It can be seen that the storage material (PCM) has a share of about 17% in the whole free cooling system. Also a viability analysis between free cooling system and the conventional refrigeration system with similar power showed that the PCM storage system (free cooling) needs an additional investment of 9%, with a payback period of 3–4 years. The electric power consumption of free cooling system was ~9.4 times lower than the conventional split type air-conditioning unit.

Although the initial investment of the PCM based free cooling system is higher compared to the conventional air conditioning units but the payback period is very less and its electricity consumptions compared to the conventional air conditioning units is almost ten times less. Utilization of free cooling systems will obviously reduce the building related CO_2 emissions due to less electricity consumption as one of the studies has estimated that replacing conventional air conditions with PCM based free cooling systems can reduce the CO_2 emissions by 430 t per year [20].

5. Indicators to access the cooling potential of free cooling systems

In this section, the indicators that have been used by different authors to access the cooling potential of free cooling system, used for the building ventilation/cooling are listed.

- *Reduction in the ventilation load* (η): Free cooling was used to reduce the ventilation load of the buildings during summer season by Takeda et al. [26] and the reduction in the ventilation load (η) was used as the performance indicator of the free cooling system. Reduction in the ventilation load (η) was calculated as

$$\eta = \frac{\sum Q_p \, \Delta t}{\sum Q_o \, \Delta t} \tag{3}$$

where Q_o is the ventilation during summer season without PCM storage and Q_p is the ventilation load with PCM storage unit.

- *Cooling degree hours* (*CDH*): Cooling degree hours was used to access the free cooling potential by Medved and Arkar [30]. CDH was calculated as

$$CDH = \sum_{i=1}^{2800} (T_a - T_o)\delta \tag{4}$$

where T_a is the ambient temperature and T_o is the air temperature at the PCM storage outlet. And, $\delta = 1$ h, when $T_a > T_o$, and $\delta = 0$ h, when $T_a \le T_o$.
Based on the calculated CDH the optimal LHTES could be selected independent of the building and its cooling demand. Therefore, the CDH represent the maximum free-cooling potential for any building.

- *Cooling capacity*: Cooling capacity (CC) was used assess the thermal performance of LHTES during comfort mode (discharging process) operation of storage unit by Waqas and Kumar [36]. Cooling capacity was calculated as follows:

$$CC = 100 * \frac{\begin{array}{c}\text{Available hours within comfort temperature range at}\\ \text{storage unit outlet during one month}\end{array}}{\begin{array}{c}\text{Total number of hours during comfort mode considered for the study}\\ (8:00\text{–}00:00) = (16 \times 30\,(31) = 480\,(496)\ \text{h})\ \text{during comfort mode operation}\end{array}} \tag{5}$$

6. Parameters influencing the thermal performance of free cooling system during charging and discharging process

In free cooling applications, air is normally used as the heat transfer fluid, transferring cold from ambient to storage during charging process while extracting the accumulated cold during discharging process. Therefore, in this section it is analyzed how air flow rate and air temperature affect the thermal performance of the free cooling systems.

1. *Effect of air flow rate on*—(i) *solidification of PCM during charging process*, (ii) *melting of PCM during discharging process and* (iii) *air temperature at the outlet of storage unit during discharging process*: It was observed by Zalba et al. [15] and Saman et al. [41] that higher air flow rate during discharging of PCM increases the heat transfer rate and storage is melted in shorter time period but at the same time it increases the outlet air temperature. For freezing of PCM during charging process, a higher air flow rate increases the heat transfer rate and shortens the freezing time [15,41]. Since in free cooling applications nighttime during which cold is to be accumulated in PCM is short so higher air flow rates can ensure the maximum charging of PCM storage. During charging process air flow rates of three to four times higher than air flow rates during discharging process are recommended for free cooling applications [29–31]. Outlet air from PCM storage can be kept within the defined comfort levels at lower air flow rates for larger time duration compared to higher air flow rates [24] during discharging process. Air flow rates of 1.0 $m^3\ h^{-1}\ kg_{PCM}^{-1}$ to 0.7 $m^3\ h^{-1}\ kg_{PCM}^{-1}$ were observed appropriate for maximum CDH during cold extraction process [29,31] for the given LHTES configuration. The Cooling Capacity (CC) [36] was maximized, for the whole summer season, at the air flow rate of 1.5 $m^3\ h^{-1}\ kg_{PCM}^{-1}$ for the studied LHTES configuration.
2. *Effect of storage unit inlet air temperature on*—(i) *solidification of PCM and* (ii) *melting of PCM*: At higher inlet air temperature during discharging process, heat transfer rate is increased resulting fast discharging of PCM storage. Conversely, during charging process, a lower inlet air temperature increases the heat transfer rates and storage is completely charged in shorter time period [15,41].

   To conclude, high temperature difference between PCM melting point and charging air is beneficial to freeze PCM in the required time period during charging process. Otherwise, high air flow rates would be needed to solidify the PCM completely in the required time period [19,20].
3. *Effect of PCM encapsulation thickness on*—(i) *solidification of PCM and* (ii) *melting of PCM*: Encapsulation thickness can greatly affect the solidification process of the PCM. Thicker capsulation of PCM will cause delay in the solidification compared to the thinner PCM capsulation at the given air flow rates. Therefore, for thicker PCM capsulation higher air flow rates may be needed to complete the solidification process in the given time period compared to the thinner PCM capsulation [15].

7. PCM melting point selection criteria for free cooling applications

Melting point of PCM plays a key role in the designing of the PCM storage unit [31] for free cooling applications PCMs should be selected in such a way that the cooled air temperature out of the storage unit during discharging process be within the range of defined comfort levels [23,24] which is between 23 °C and 27 °C for summer season Therefore, for free cooling systems, the melting temperature of the PCM should be between 19 and 24 °C [24]. Different authors have provided different criteria to choose the melting point of PCM which are elaborated below:

- Melting point of the PCM should be chosen in such a way that it ensures maximum solidification of PCM during charging process and during daytime it should be able to keep air temperature within comfort levels. According to Yanbing et al. [21] the melting point of the PCM must be close to the designed room temperature.

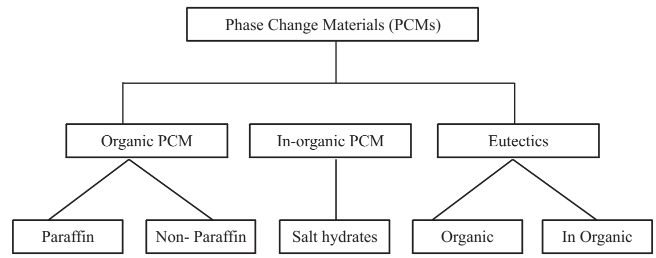


Fig. 15. Types of phase change materials [42,43].

- For the buildings which are located in warmer climates the PCMs with a higher melting temperature are more suitable for maximizing the cooling potential of the free cooling system [30]. According to Medved and Arkar [30] the optimal melting temperature for free cooling application can be found from the following relation:

$$T_p = \overline{T}_a + 2K \tag{6}$$

  where T_p is the PCM peak melting temperature and T_a is the average ambient temperature.
- According to Lazaro et al. [34], for free cooling applications, to maintain a specific temperature level when the cooling demand is high, the PCM phase change temperature should be lower. On the other hand, for very low cooling demand, the phase change temperature should be close to the objective temperature level.
- Another study [36] suggests that cooling potential of the free cooling, in dry and hot climatic conditions, can be maximized by using PCM having melting point equal to the comfort temperature of the hottest summer month.

To conclude the above the discussions the selection of the melting point of the PCM especially for free cooling application, depend upon the comfort temperature or the mean temperature of the summer months.

8. Types of PCMs and their encapsulation for free cooling applications

This section mainly explains the type of PCMs that are being and can be used for building application especially in free cooling application. Since commercially available has PCM been used by different researchers therefore the manufacturer of these PCMs are also elaborated in this section. In the end encapsulation techniques of PCM are discussed.

PCMs are generally divided into three main categories, organic PCMs, inorganic PCMs and eutectics of organic and inorganic compounds [42–45] as shown in Fig. 15. For free cooling application, PCM selection depends on the climatic conditions where it is being used and the desired temperature of the cool air needed from storage outlet [24]. Moreover, PCMs to be used for free cooling applications should posses the following properties also [17,38,43–50]:

(i) Thermo-physical properties
   - Melting temperature of the PCM should be in the desired operating temperature range.
   - Thermal conductivity should be high to assist in charging of PCM within the limited time period.
   - It should have higher latent heat per unit volume so that the storage size to store the given amount of energy is less.
   - It should have high specific heat capacity that can be beneficial for the additional sensible heat storage.

Table 1
PCM used for free cooling application in literature.

Compound	Type of PCM	Melting point (°C)	Latent heat (kJ/kg)	Reference
$Na_2SO_4 \cdot 10H_2O$	Salt hydrate	21	198	[19,20]
RT25	Paraffin	24	164	[22]
RT20	Paraffin	20–22	172	[14,23,24,29–31]
FMC	Paraffin	20–23	130	[28]
GM (granules)	65% ceramic material+35% paraffin	23.5–24.9	41.9	[26,27]
SP 27 A 8	Blend	27	180	[36]

- There should be small volume changes during phase change process to prevent thermal expansion of the containers.

(ii) Chemical properties
- PCMs should have a long-term chemical stability.
- PCMs should be non-corrosive with the container or enclosure.
- PCMs should be non-toxic, non-flammable and non-explosive.

(iii) Kinetic properties
- No super-cooling or sub-cooling should occur during liquefaction and solidification processes.
- It should have high crystallization rate.

In addition, low cost and the availability of the PCM is also vital.

Paraffinic PCMs have been used by many researches [22,23,28–32] as a thermal storage material for the storage of cold for free cooling as described in Table 1. One of the major reasons of using paraffin PCM is their very little or no sub-cooling and non-corrosive nature. Subcooling is a process which normally occurs in salt hydrate in which PCM has to be cooled down well below melting point before the PCM starts solidify [51]. Due to subcooling, PCM requires extra time during solidification process. Major issue with the paraffin PCM is their low thermal conductivity which is a major barrier in their wide spread usage.

Inorganic PCMs in general have a rather high heat of fusion and good thermal conductivity. These are cheap and non-flammable also compared to paraffin PCMs. However, most of them are corrosive to metals and undergo sub-cooling process.

PCMs that have been used frequently for free cooling applications are listed in Table 1. It can be observed from Table 1 that commercially available PCMs have been frequently used, due to their availability, within the different melting point (20–27 °C). Most of the studies [14,22–24,28–31] have used the PCMs of paraffin type while some have used [26,27] granules PCM and very few have used the salt hydrates PCM (shown in Fig. 16).

Main reason for preferring the paraffinic PCMs is that they do not rust and react with the encapsulated material. Therefore, the chances of leakage problem are very less. Another advantage of the paraffinic PCMs is that subcooling is very less (or even does not exists) compared to salt hydrates. Major disadvantage of using paraffinic PCMs is that their thermal conductivity is very less compared to salt hydrates due to which some heat transfer enhancement techniques are used within PCM encapsulation. Some PCMs including organic, inorganic and commercially available that can be used for free cooling applications are listed in Table 2.

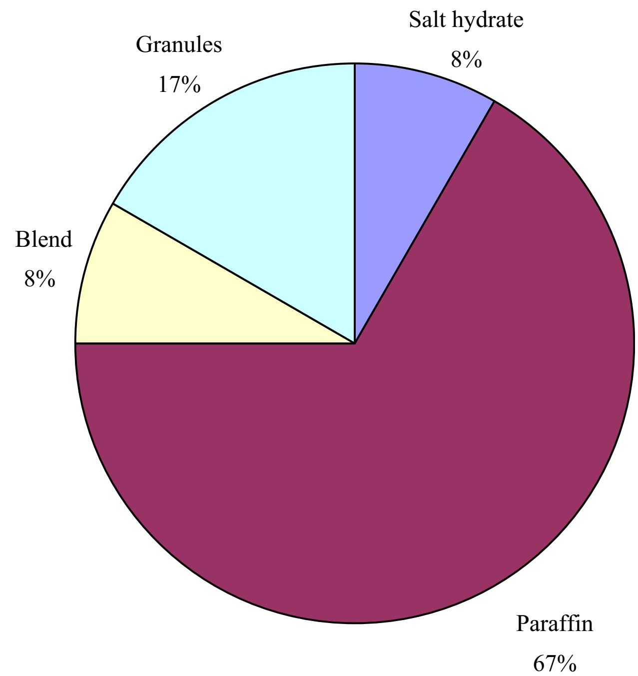


Fig. 16. Type of PCMs used for free cooling in different studies. *Source*: [14,19,20,22–24,26–31,36]

8.1. Manufacturers of PCMs around the world

Commercially available PCMs have been used frequently for free cooling applications of the buildings [14,19–24,26,28–32]. The manufacturers/suppliers of theses commercially used PCM around the world are summarized in Table 3. It can be observed from Table 3 that there are very few manufacturers of PCM around the world (only seven) producing PCMs for heating and cooling of buildings and most of these manufacturers are European based. Due to the limited manufacturers, the price of the PCM is still very high.

8.2. PCM encapsulation techniques for free cooling application

PCMs change phase from solid to liquid or from liquid to solid during cold extraction and cold accumulation process; therefore, it should be contained within the containers. Two types of PCM encapsulation are commonly used—micro-encapsulation and the macro-encapsulation [47]:

- *Micro-encapsulation method*: In micro-encapsulation, very small PCM particles are enclosed in a very thin and solid shell. The size of these particle ranges from 1 μm to 1000 μm. These PCM particles can then be incorporated in any matrix that is well matched with the encapsulated shell.
- *Macro-encapsulation*: The second method is macro-encapsulation, which means the inclusion of PCM in some form of package such as tubes, small bags, spheres, panels or other containers. These containments can contain milliliters to several liters of PCM and the containers serve directly as heat exchangers. Details of the PCM encapsulation methods/techniques are available in [38,43,45,47].

Table 2
Candidate PCMs for free cooling applications.

Name of PCM	Type of PCM	Melting point (°C)	Latent heat (kJ/kg)	Reference
Butyl stearate	Fatty acid	19	140	[70,71,72]
Propyl palmitate		19		[70,71]
Emerest 2325	Fatty acid	20	134	[73]
Emerest 2326	Fatty acid	20	139	[74]
82% Capric acid+18% Lauric acid	Fatty acid	19–24		[75]
50% Butyl stearte+48% Palmitate	Fatty acid	20		[74,76]
45% $CH_3(CH_2)_8COOH$ 55% $CH_3(CH_2)_{10}COOH$ 45/55 Capric–lauric acid	n.a.	21	143	[70,71,44]
$CH_3(CH_2)_{11}OH$	n.a.	26	200	[70,71]
n-Octadecane	n.a.	27		[77]
Inorganic PCMs				
$KF \cdot 4H_2O$	Salt hydrate	18.5	231	[78,79,80]
$FeBr \cdot 3.6H_2O$	Salt hydrate	21.0	105	[17]
$Mn(NO_3) \cdot 2.6H_2O$	Salt hydrate	25.8	125.8	[43,80]
48% $CaCl_2$+4.3% NaCl+0.4% KCl+47.3% H_2O	Salt hydrate	26–28	188	[81]
$CaCl_2 \cdot 6H_2O$	Salt hydrate	29	190.8	[41,54,55,79,82,82]
Commercially available PCM				
ClimSel C 21	Compound	21	122	[14,23,24]
GR 25	Granule	23–24		[83,84,85]
ClimSel C 24	Compound	24	180	[14,23,24]
SP22 A4	Blend	24	165	[23]
SP 25 A 8	Blend	25	180	[86,87]
SP22 A17	Blend	22	180	[87]
RT27	Paraffin	27	184	[87]
RT21	Paraffin	22	134	
A26	Paraffin	26	150	[88]
A24	Paraffin	24	145	[88]
A22	Paraffin	22	145	[88]
Latest™25T	Salt hydrate	24–26	175	[89]
Latest™29T	Salt hydrate	28–29	175	
S27	Salt hydrate	27	183	[88]
S25	Salt hydrate	25	180	
S23	Salt hydrate	23	175	
S21	Salt hydrate	22	170	

Table 3
PCM manufacturers around the world.

Company	Country of origin	Products	Product ID
Rubitherm GmbH [85]	Germany	Salt hydrates/ Blend Paraffins Powder Granules	SP RT PX GR
Merck KGaA [90]	Germany	Salt hydrates	–
Climator AB [91]	Sweden	Salt hydrates	ClimSel C
Cristopia Energy Systems.[92]	France	Salt hydrates	AC
PCM Energy [89]	India	Salt hydrates	Latest™
Mitsubishi Chemical [93]	Japan	Salt hydrates	STL
EPS Ltd [88]	UK	Praffin, salt hydrates and eutectics	PlusICE

Due to high investment cost of micro-encapsulation technique and sophisticated equipments required to fabricate, macro-capsulation is preferred and widely used for free cooling applications as shown in Fig. 17. Zalba et al. [15] used the flat plates for PCM encapsulation made with methacrylate to allow for the phase change visualization which were about 15 mm thick. While Hed and Bellander [18] used 8 mm thick aluminum pouches for PCM encapsulation, which were 80 mm wide and 160 mm long. Similarly, polyethylene spheres having the diameter of 50 mm were used for PCM capsulation by Arkar et al. [29–31]. PCM encapsulation is also used as a heat exchanger to transfer the heat between heat transfer fluid and PCM during charging and discharging process which is explained below:

- *PCM–Air heat exchangers used for free cooling applications*: Heat exchanger geometries used by different authors for free cooling applications are tabulated in Table 4 and the main parameters of these heat exchangers are discussed and explained below:
  - Turnpenny et al. [19] used the heat pipes embedded in cylindrical PCM container at the air flow rate of 28 m^3/h per kg of PCM, PCM was solidified within in 11.5 h and the melted in 10 h.
  - Zalba et al. [15] proposed the flat plate heat exchanger with PCM encapsulated as flat slabs. Using this type of heat exchanger PCM was completely solidified within 4 h and the melting of PCM was completed within 5.5 h.
  - Arkar et al. [31] used the cylindrical storage type heat exchanger with PCM encapsulated in plastic sphere of

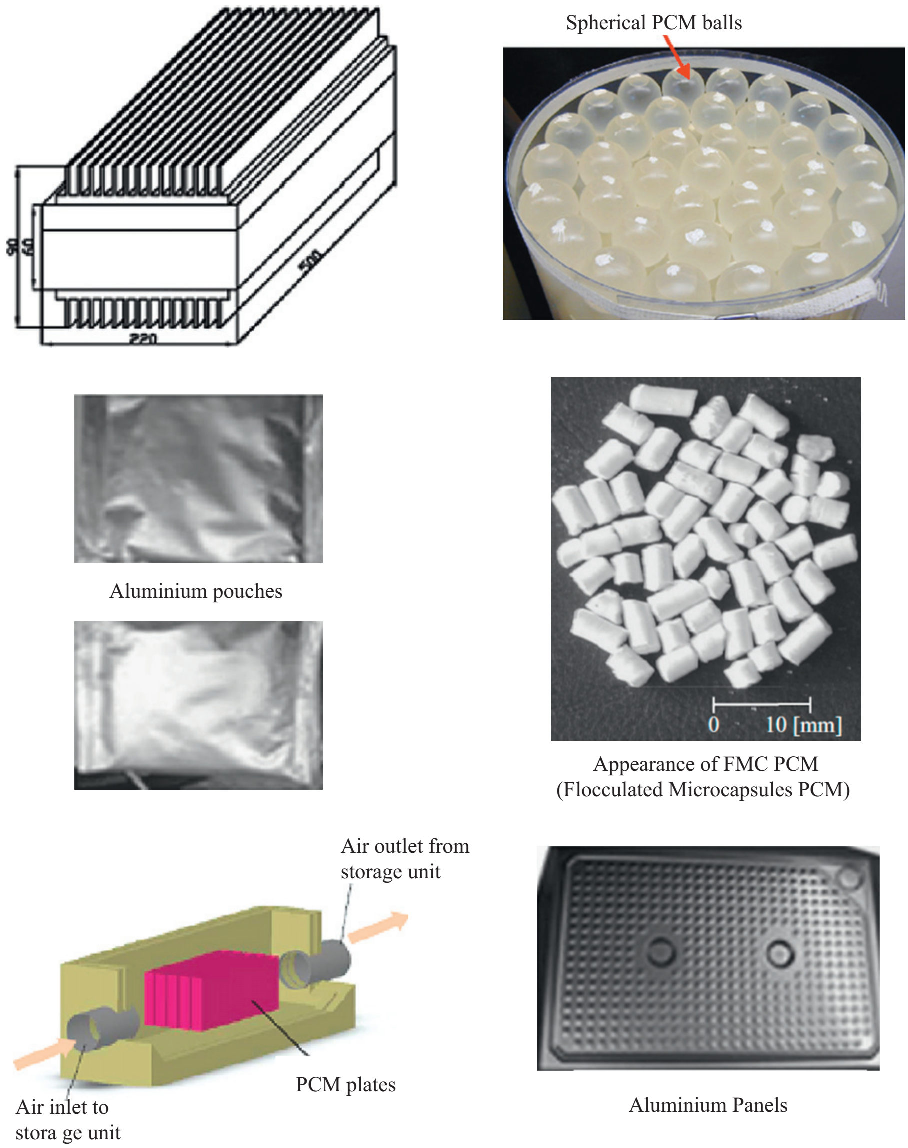


Fig. 17. PCM capsulation used for free cooling applications.

Table 4
Studies on different PCM–air heat exchangers.

Parameters		References					
		[19]	[15]	[31]	[24]	[32]	
Heat exchanger type		Heat pipes embedded in PCM storage unit	Plate heat exchanger	Cylindrical storage type (PCM packed bed)	Duct type	Duct type	Duct type
PCM encapsulation		n.a.	Flat slabs	Plastic spheres	Aluminum container with fins	[a]Aluminum pouches	[b]Aluminum panels
Storage capacity (kJ)		2300	600	n.a.	732	31.6	24.4
Storage density		60,000	100,000	n.a.	~109,000		
$\dot{V}$ (air flow rate) (m^3/h/kg of PCM)		~28	33	4.0	10	n.a.	n.a.
$T_{air\text{-}in}$–T_{PCM}	charging	~10 K	6 K	n.a.	n.a.	n.a.	n.a.
	Melt	~17 K	6 K	13 K	4 K	n.a.	n.a.
$t_{solidification}$ (h)	~11.5	3.9	n.a.	n.a.			
t_{melt} (h)	~10	5.6	5	3.6	4.5	2.7	

n.a.: not available.
[a] Filled with inorganic PCM having thermal conductivity of 0.7 W/(mK).
[b] Filled with organic PCM having thermal conductivity of 0.16 W/(mK).

50 mm diameter. In this case temperature difference of 13 K was used to complete the melting time of PCM within 5 h.
- Butala and Stritih [24] used the duct type heat exchanger with finned PCM metallic container. Affect of fins was quite clear as the melting of PCM was completed within 3.6 h with temperature difference of only 4 K.
- Lazaro et al. [32] used duct type of heat exchanger with two different types of PCM capsulation containing different PCMs—organic and inorganic. Difference in the melting time period is due to the difference in the thermal conductivity of the used PCMs.

Main purpose of Table 4 is to evaluate which heat exchanger is more suitable to be used for free cooling application that has been used by different researchers. From information tabulated in Table 4 it may be concluded that flat slab configuration has the highest energy storage density compared to the other configurations. So this geometry may be appropriate for PCM–air heat exchangers for applications where storage density is important and only low temperature difference between air and PCM are available, such as in free-cooling applications of the buildings. But it is difficult to make any decision regarding any configuration as very less data is available regarding these heat exchangers.

9. Numerical techniques to study the cold released and accumulated by PCM storage and change in air temperature due to this

Mathematical modeling for PCMs for free cooling of buildings involves greater complexity due to phase change phenomenon as the solid and liquid boundary changes its positions continuously as heat is extracted from PCM or absorbed by PCM. A detailed and comprehensive review on the numerical modeling and simulations related to phase change material has already been conducted by Dutil et al. [52,] and Verma et al. [53]. The main purpose of this section is to elaborate the numerical methods mainly used for PCM based free cooling applications briefly. There are several methods being used to model and study the heat transfer mechanism in PCM and heat transfer fluid. The numerical methods for such problems are reported in two broad categories, such as temperature model [41,54,55] and Enthalpy model [18,56,57].

- In the Temperature based model, the phase change boundary is either captured on a grid at each fixed time step while using a non-uniform grid spacing, or captured on a uniform grid, and therefore, a non-uniform time step is used [58].
- While in the enthalpy model, the phase change boundary is totally eliminated by formulating the energy equation in terms of enthalpy where a fixed grid size and fixed time step can be used. Also, in this method a single equation for the PCM is sufficient to find the temperature variation of the PCM which melts/solidifies at a particular range of temperature [58,53]. Solution of these numerical model is based on the finite difference method using explicit or implicit techniques for numerical resolution [60]:
- The explicit method is straightforward and easy to program but is conditionally steady. It needs to have a time step smaller than a limit value in order to avoid any divergence. On the other hand it increases simulation time.
- The implicit method is more complex to program but it is unconditionally steady. There is no limit for the time step except if we would like good calculation accuracy.

The mathematical model to study the heat transfer mechanism in PCM and change in air temperature as is pass through PCM storage (for free cooling application) was studied by Hed and Bellander [18]. PCM storage unit was modeled as duct with air flowing through it as shown in Fig. 18. Finite difference method was used to solve the differential equations. Model depends on a temperature based heat capacity method. Heat balance for an element dx:

$$uA\rho c\big(T(x)-T(x+dx)+P\,dxU_p(T_{PCM}-T(x))\big)=0 \tag{7}$$

The solution of the governing differential equation is, where $T(0)=T_0$ which is the inlet air temperature:

$$T(x)=T_{PCM}+(T_0-T_{PCM})e^{-(PU_P/uA\rho c)x} \tag{8}$$

The heat exchanger is programmed as a single node finite difference model. The temperature in the PCM node for each time step i is calculated using the following expression:

$$TP_{i+1}=TP_i+\frac{dt}{c_P(T)m_P}\left[uA\rho c\left(1-e^{-PU_PL/uA\rho c}\right)\right](TE(t)-TP_i) \tag{9}$$

The outlet air temperature for each time step i was calculated using:

$$TX_i=TPi+e^{-PU_PL/FL\rho c}(TE(t)-TP_i) \tag{10}$$

To validate the numerical results, test runs were performed with the prototype heat exchanger at constant temperature. The inlet air temperature is fed into the finite-difference model. The results of measurement and calculation agree reasonably well. Effective heat capacity method to study the heat transfer mechanism with PCM has been used by Tzivanidis et al. [37] also in which heat transfer fluid used by the author was water instead of air.

The mathematical model employed by Saman e al. [41,54,55] to study the heat transfer mechanism in air based PCM storage unit is based on the so-called enthalpy formulation where the dependent variable is enthalpy. The strength of the technique lies in the method of updating the liquid fraction from the sensible enthalpy field. For a phase change process involving either melting or freezing, energy conservation can be expressed in terms of total volumetric enthalpy and temperature as follows [61] by assuming the constant thermo-physical properties of materials undergoing phase change:

$$\frac{\partial H}{\partial t}=\nabla(k(\nabla T)) \tag{11}$$

In the above equation the total volumetric enthalpy "H" is the sum of the sensible and latent heats of the PCM and is related to the temperature of the PCM as follows [36,41,54,55]:

$$H=\begin{cases}\rho_{pcm}C_{pcm}(T_{pcm}-T_m) & \text{for } T_{pcm}<T_m \text{ Solid region}\\ \rho_{pcm}C_{pcm}(T_{pcm}-T_m)+\lambda\rho_{pcm} & \text{for } T_{pcm}>T_m \text{ Liguid region}\end{cases} \tag{12}$$

From above equation, if the PCM is in solid phase, then the latent heat of the PCM is zero and volumetric enthalpy is only sensible heat. If the PCM is in liquid phase, then the total volumetric enthalpy is the combination of latent heat and sensible heat. After calculating the total volumetric enthalpy, the temperature of the phase change material is calculated using the following equations:

$$T_{pcm}\begin{cases}T_m+\frac{H}{\rho_{pcm}C_{pcm}} & \text{for}\quad 0<H\\ T_m & \text{for}\quad 0<H<\rho\lambda\\ T_m+\frac{H-(\rho_{pcm}.\lambda)}{\rho_{pcm}C_{pcm}} & \text{for}\quad H>\rho\lambda\end{cases} \tag{13}$$

After calculating the storage material temperature using Eq. (13) and enthalpies from Eq. (12), the liquid fraction (L.F.) is calculated. Liquid fraction informs whether the PCM is in solid, liquid or in the mushy phase. L.F. = 0 indicates that the material is in the solid phase, while L.F. = 1 refers to the material in liquid

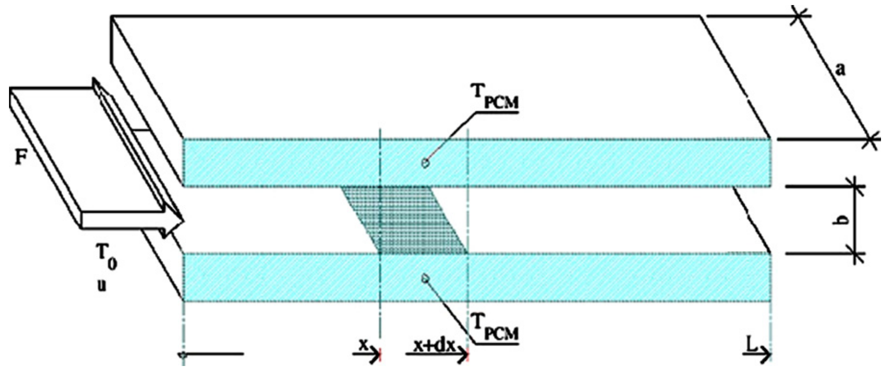


Fig. 18. Model used for establishing the governing differential equation of the PCM heat exchanger [18].

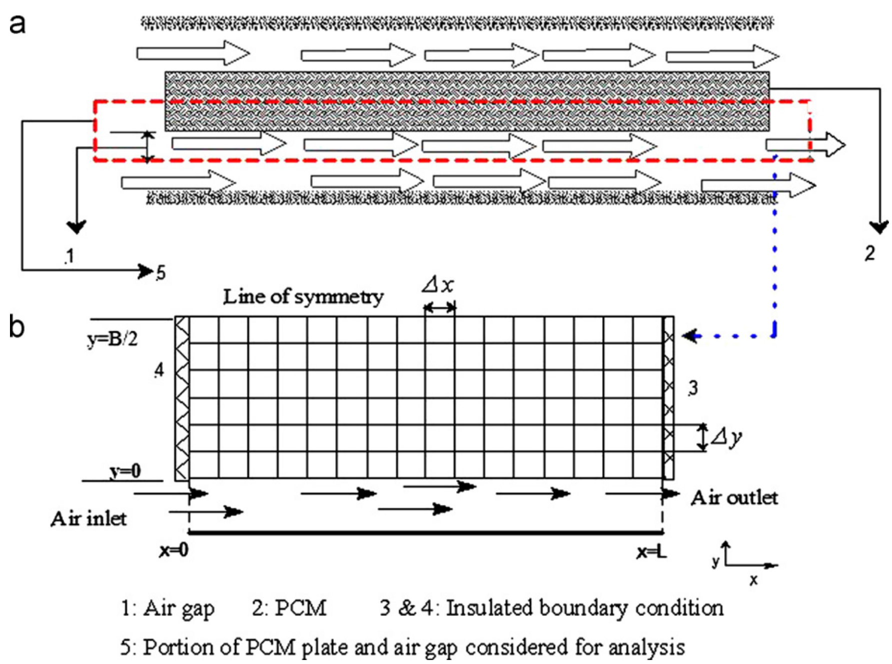


Fig. 19. (a) Section of the PCM storage unit and air flow path to be analyzed and (b) two dimensional grid with boundary conditions.

form. If $0 < L.F. < 1$, the PCM is in mushy region. This is calculated using Eq. (14) as follows:

$$L.F.(H) = \begin{cases} 0 & \text{for} \quad H \le 0 & \text{solid phase} \\ \frac{H}{\rho_{pcm}\lambda} & \text{for} \quad 0 < H < \lambda\rho_{pcm} & \text{mushy region} \\ 1 & \text{for} \quad H > \lambda\rho_{pcm} & \text{liquid phase} \end{cases} \tag{14}$$

The change in air temperature as it flows through the PCM storage can be calculated from the following heat balance equation:

$$Q = \dot{m}_{air} C_{p\ air}\ \Delta T_{air} = hA_{HT}\left(T_{pcm} - T_{air}\right) \tag{15}$$

where Q is the rate of heat transfer to or from heat transfer fluid, h is the heat transfer coefficient and A_{HT} is the surface area of the boundary node. For more details, readers are referred to articles [41,54,36] for this numerical method. The above mentioned equations are solved using finite difference technique using explicit numerical resolution method by Waqas and Kumar [36] while Saman et al. [41,54,55] used implicit numerical resolution method. Fig. 19 shows the numerical grid used by Waqas and Kumar [36] for solution of above mentioned equations.

A cylindrical LHTES containing spheres filled with paraffin was developed by Arkar and Medved [62] to use the solar energy and the coldness of ambient air to reduce the energy used for heating and cooling by domestic buildings. A packed bed numerical model was used to take into account the non-uniformity of the PCM's porosity and the fluid's velocity. The basic assumption of this model was that the PCM capsules behave as a continuous medium and not the individual particles. The governing equations for this model are:

$$\varepsilon(r)\rho c_P \frac{\partial T}{\partial t} + u(r)\rho_f c_f \frac{\partial T}{\partial x} = \lambda_{fx}\frac{\partial^2 T}{\partial x^2} + \lambda_{fr}\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) + \alpha_{eff}(r)a_P(r)(\Theta - T) \tag{16}$$

For PCM the governing equation is

$$(1-\varepsilon(r))\rho_{PCM} c_{app}(\Theta)\frac{\partial \Theta}{\partial t} = \alpha_{eff}(r)a_P(r)(T-\Theta) \tag{17}$$

The initial and boundary conditions according to Fig. 20 are:

$$\begin{array}{llllll} \multicolumn{6}{l}{\text{at } t=0 \quad T=\Theta=\text{Constant}} \\ \text{I} & x=0; & 0\le r\le R; & t>0 & T=T(t) & \frac{\partial\Theta}{\partial x}=0 \\ \text{II} & r=0; & 0\le x\le L; & t>0 & \frac{\partial T}{\partial r}=0; & \frac{\partial\Theta}{\partial r}=0 \\ \text{III} & x=L; & 0\le r\le R; & t>0 & \frac{\partial T}{\partial x}=0; & \frac{\partial\Theta}{\partial x}=0 \\ \text{IV} & r=R; & 0\le x\le L; & t>0 & -\lambda_{fr}\frac{\partial T}{\partial r}=U_w(T_a-T); & \frac{\partial\Theta}{\partial r}=0 \end{array} \tag{18}$$

Above mentioned equation were solved numerically using a finite-difference approximation (explicit method). For more details,

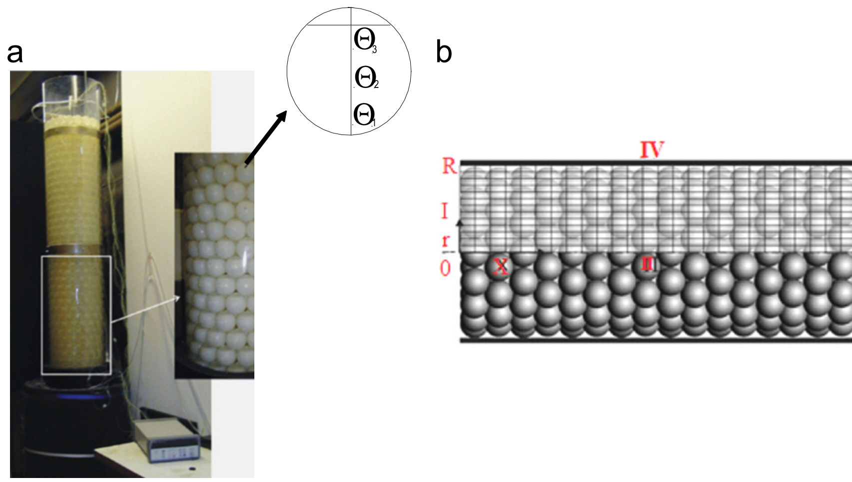


Fig. 20. Experimental setup and numerical technique used by Arkar et al. [29–31,62] and Xia et al. [63] to study the heat transfer related issues in PCM and heat transfer fluid.

readers are referred to articles [29–31,62,63] for more details for this numerical method.

10. Key issues and challenges for PCM based free cooling concepts

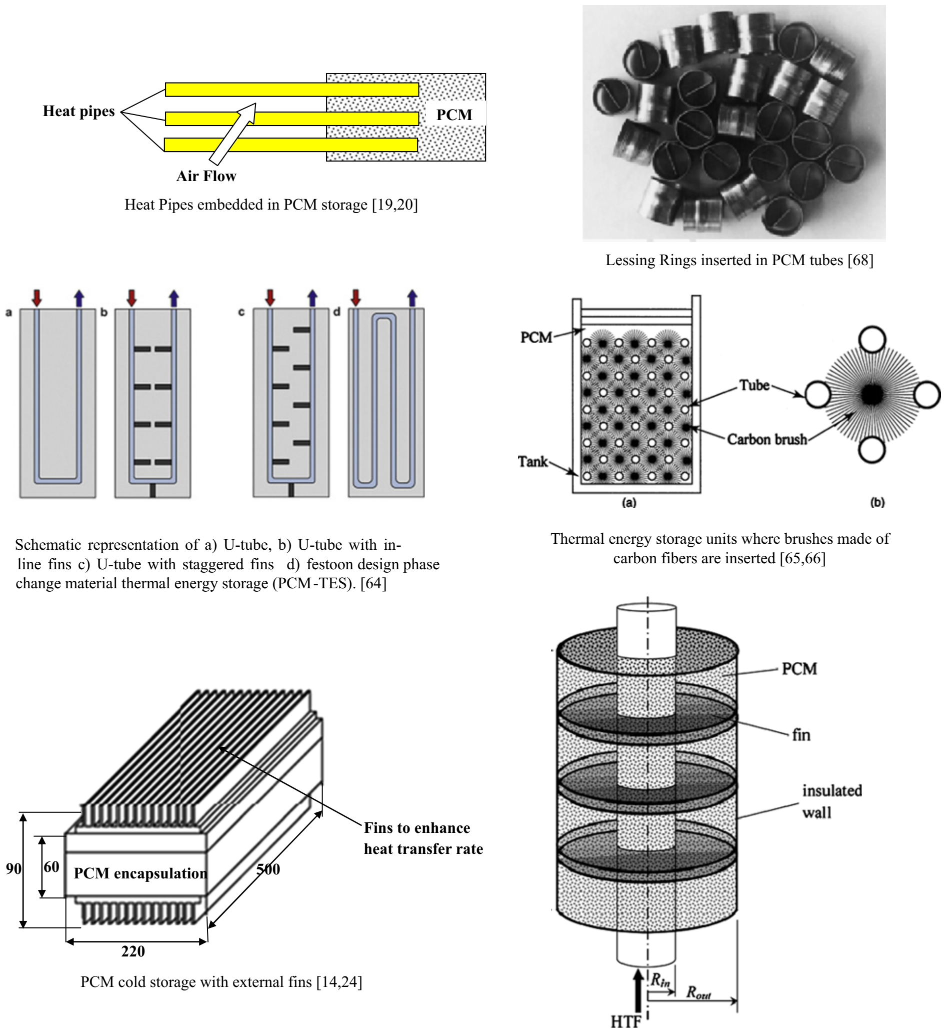
Although PCM based free cooling of buildings may seem an attractive option compared to conventional ways of building cooling techniques yet there is still much to be explored to improve the working of such systems. One key problem is the way heat is transferred between air which is heat transfer fluid and PCM. It can happen that the PCM will not solidify completely in the desired time, therefore an appropriate design of the heat exchangers and also mode of operation are essential. Some of the key issues that need to be addressed while designing the or working for PCM based free cooling system are elaborated below:

- One of the key issue that is needed to be addressed is that most phase-change materials (PCMs) with high energy storage density have an unacceptably low thermal conductivity and hence heat transfer enhancement techniques are required for any latent heat thermal energy storage (LHTES) applications. In order to compensate the low thermal conductivity heat transfer enhancement techniques like introduction of external and internal fins [14,24,64], carbon fiber bushes were inserted in PCM storage [65,66], PCM in a shell and tube geometry with radial fins [67] and lessing rings of 1 cm diameter was used by Velraj et al. [68] to enhance the heat transfer rate between PCM and heat transfer fluid as shown in Fig. 21.
- Due to high storage density hydrated salts are commonly used in PCMs as a storage material but the main problems of phase segregation and sub-cooling during solidification and melting processes have limited their application [47]. Bentonite clay was suggested to overcome the problem of phase segregation but this may decrease the rates of crystallization and heat transfer to the salt due to the lower thermal conductivity of the mixture [47]. Borax has been long suggested by Telkes [69] as a nucleating agent to minimize subcooling. However, this required some thickening agent to prevent settling of the high density borax. In spite of the problems associated with the application of hydrated salts in thermal storage systems, a number of firms have put significant efforts in developing nucleating agents and stabilizers for some of the hydrated salts. Although Paraffin PCMs shows very low thermal conductivity compared to other types of PCM yet they are preferred over salt hydrates as salt hydrates may have the problem of sub-cooling, phase seggregation and their nature to rust with the container material.
- Another problem is also the amount of PCM needed for thermal storage. Studies have shown that the range is somewhere between 6.5 and 30 kg per m^2 of floor plan area depending on the material, climate, cooling system, thermal load, etc. [29,68]. This means that the quantity of the material required for buildings would be enormous which is not considered really in favor of the PCM and needed to be addressed during further research.

11. Summary of the free cooling studies

The distinguished features of the free cooling studies discussed above are grouped in Table 5 and summarized below:

- Free cooling of buildings coupled with PCM storage unit performs efficiently in the climatic conditions where the diurnal temperature range is between 12 °C and 15 °C.
- Air is the heat transfer fluid whenever PCM storage is used for free cooling application of buildings. Charging of PCM (solidification process) is carried out at nighttime and the accumulated cold is extracted during hot day times.
- Air flow rate during charging process should be higher as compared to discharging process [22]. It is found that air flow rate during charging process is about three to four times higher as compared to discharging time period [29].
- Melting point of PCM plays an important role in design of the storage unit [31]. Melting point should be chosen in such a way that it ensures maximum solidification during charging process and during daytime it should be able to keep air temperature within comfort levels. Moreover, melting point of the PCM must be close to the designed room temperature [21]. Melting point of PCM used for free cooling applications is found in the range of 20–26 °C.
- PCM thermal conductivity k has a strong effect on the system performance. PCM with k as high as possible should be selected, which will facilitate the charging and discharging of PCM within limited nighttime [37].



Heat Pipes embedded in PCM storage [19,20]

Lessing Rings inserted in PCM tubes [68]

Schematic representation of a) U-tube, b) U-tube with in-line fins c) U-tube with staggered fins d) festoon design phase change material thermal energy storage (PCM-TES). [64]

Thermal energy storage units where brushes made of carbon fibers are inserted [65,66]

PCM cold storage with external fins [14,24]

PCM in a shell and tube geometry with radial fins [67]

Fig. 21. Heat transfer enhancement techniques for PCMs.

– Cooling degree hours (CDH) [30], reduction in ventilation load (η) [28] and cooling capacity (CC) [26] have been used as the performance indicators of the free cooling systems.
– Free cooling system of equal power of conventional air conditioning unit uses ~9% less electricity but its initial cost is ~10% higher with payback period of 3–4 years [22].
– Short summer nights, during which PCM is to be charged, is the major climatic barrier, which should be kept in focus during the design of the PCM storage unit for free cooling applications [36].

12. Further research areas

- PCMs used for free cooling applications have very low thermal conductivity which can result in slow charging of PCM during the limited nighttime period. In order to maximize the PCM solidification and compensate the low thermal conductivity, efficient and economical heat transfer enhancement techniques are needed to be explored.
- Reduction of building ventilation and cooling due to PCM based free cooling systems is analyzed theoretically and numerically in most of the studies [19,26,29–31] and there is hardly any study in which the free cooling system is applied in real case for building ventilation and cooling except [20] where a prototype PCM storage was used for free cooling. Therefore, it is needed to evaluate the capability of the free cooling system to reduce the building cooling and ventilation load in real cases.
- Most of the studies are conducted for European climatic conditions where daytime temperature does not rise to very high degrees. None of the study is found for the desert climatic conditions where night temperatures can be as low as 20 °C and daytime temperatures can rise as high as 45 °C. Therefore, it is needed to explore how free cooling thermal performance will differ in such climatic conditions than European summer conditions.

13. Conclusions

PCM based free cooling of building is one of the emerging passive way of building ventilation and especially in the climatic conditions where diurnal temperature range is between 12 and 15 °C. Studies have shown the effectiveness of free cooling techniques in reducing the ventilation and the cooling loads of

Table 5
Summary of recent theoretical and experimental studies based on free cooling of buildings.

Reference	Type of study		For climatic condition	PCM properties		Heat exchanger	Important results/findings
	Theoretical study	Experimental study		Type	Melting point (°C)		
[32]	Experimental work based on the outcomes of [22]		Lab scaled experiments	Inorganic PCM and organic PCM	25.0–27.0	Vertical duct type. Aluminum pouches and aluminum panels were used as PCM containers	• Aluminum panel encapsulation of PCM is more suitable for free cooling purpose. • Efforts should be made to design efficient heat exchangers instead of enhancing the PCM thermal conductivity. • Thermal conductivity enhancement of PCM puts an additional increase in the cost of the PCM.
[19]	✓	✓	UK	$Na_2SO_4 \cdot 10H_2O$ (salt hydrate)	22.0	Heat pipes embedded in PCM storage unit	• High temperature difference between PCM melting point and charging air will beneficial to freeze and melt PCM in the required time period otherwise high air flow rates will be needed to solidify the PCM completely in the required time span.
[21]	✓	✓	China	Fatty acid	24.5–25.5	PCM packed bed storage	• Night ventilation technique coupled with PCM storage can increase the comfort level of the buildings during day time as 300 W cold was discharged from PCM to the living room. COP of the NVP was found 80.
[22]		✓	Laboratory experiment	RT25 paraffin	25.0	Flat plate heat exchanger	• Thickness of PCM slabs plays a vital during solidification process during nighttime.
[23]	✓	✓	Lab scale experiment	RT20 paraffin	22.0	PCM in finned rectangular container	• For small spaces the cooling load is lower so air flow rate will also be lower. • For large spaces the cooling load will be higher and higher air flow rate will be needed. • Connecting cold storages in parallel will fulfill the required cooling load.
[26]	✓	✓	Japan	Granule PCM (GR)	22.5–25.0	PCM packed bed storage	• Climatic data should be considered for the selection of Phase change temperature of PCM. • Ventilation load can be reduced from 46% to 62%, using PCM storage unit in different cities of Japan.
[28]	✓	✓	Japan	Flocculated microcapsules PCM (paraffin)	20.0–23.0	PCM packed bed storage	• Stored cold during in PCM night time can be used to achieve a cooling load reduction of 92% during following daytime.
[30]	✓	✓	European climate	RT20 paraffin	20.0	Packed bed model (cylindrical storage unit filled with PCM spheres)	• PCM melting temperature should be equal to the average temperature of the hottest summer month. • Air flow rate during charging of PCM should be at least three times higher than discharging air flow rate.
[31]	✓	✓	European climate	RT20-26 paraffin	20.0–26.0	Packed bed model (cylindrical storage unit filled with PCM spheres)	• For efficient performance the PCM melting temperature should be in the range of $\pm 2^\circ$ C from the operating temperature.
[29]	✓	✓	European climate	RT20 paraffin	20.0	Packed bed model (Cylindrical storage unit filled with PCM spheres)	• 6.4 kg of PCM per m^2 of the floor area was found optimum for the selected location. • Comfort temperature of the building was kept between 25° C and 26° C.
[36]	✓		Dry and hot climatic conditions	SP27	27–29	Flat plate heat exchanger	• When melting point of the storage material is equal to the comfort temperature of the hottest summer month, performance of the storage unit in terms of cooling capacity is maximized for the whole summer season. • The performance of the storage unit is more sensitive to phase change temperatures of the PCM as compared to air flow rates.

the buildings during summer season. PCM storage is the key component in the free cooling system and care should be taken while selecting PCM and PCM melting point. PCMs are still under research and development phase. Due to which the initial cost of the PCM based free cooling system is still high and the technology is still not commercialized. More commercialization of the PCMs is needed to keep the free cooling systems price competitive with other conventional cooling and ventilation technologies. Also if such systems are used instead of conventional ventilation and air conditioning systems electricity consumption will be reduced which will directly reduce the building generated CO_2 emissions.

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